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# The First-Order Effect of Holocene Northern Peatlands on Global Carbon Cycle Dynamics

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**Abstract.** Given the fact that the estimated present-day carbon storage of Northern Peatlands (NP) is about 300-500 petagram (PgC, 1 petagram =  $10^{15}$  gram), and the NP has been subject to a slow but persistent growth over the Holocene epoch, it is desirable to include the NP in studies of Holocene carbon cycle dynamics. Here we use an Earth system Model of Intermediate Complexity to study the first-order effect of NP on global carbon cycle dynamics in the Holocene. We prescribe the reconstructed NP growth based on data obtained from numerous sites (located in Western Siberia, North America, and Finland) where peat accumulation records have been developed. Using an inverse method, we demonstrate that the long-term debates over potential source and/or sink of terrestrial ecosystem in the Holocene are clarified by using an inverse method, and our results suggest that the primary carbon source for the changes (sinks) of atmospheric and terrestrial carbon is the ocean, presumably, due to the deep ocean sedimentation pump (the so-called alkalinity pump). Our paper here complements ref. 1 by sensitivity tests using modified boundary conditions.

## 1. Introduction

Holocene carbon cycle dynamics over the past 8000 years before present (8 kyr BP) have been a puzzle to the paleoclimate community [2-9]. There have been long-term debates of different roles of terrestrial and oceanic carbon systems in the Holocene. Many efforts to better understand Holocene carbon cycle dynamics have been focused on the sea surface temperature changes [2, 5-7, 9-10], deep ocean adjustments [3, 5, 7, 11-12], natural sources of terrestrial carbon cycles [2, 5-7], and anthropogenic land-use and land-cover changes [13-15]. A common feature of these efforts is the neglect of the slow but persistent carbon accumulation of NP.

The end of the last deglaciation was accompanied by the initiation and growth of NP [16-25]. Carbon storage in present-day NP is about 300-500 PgC [17-18, 21-23, 26-28]. The main uncertainties to include the NP into players of Holocene carbon cycle dynamics are: 1) average basal dates of NP [21-22], 2) bulk carbon densities of NP [29-30], and 3) mean peat depths of NP [27, 31].

Here we make an effort to include the first-order effect of peatlands on global carbon cycle dynamics in the Holocene by prescribing an idealized development of NP, based on recent work of refs. 21-22, 24, and 27. Our inverse method was first developed in ref. 7 (see Section 3 and figure 1 for details). The fundamental bases of our approach are: 1) the global carbon budget is conserved under the timescale of interests; 2) there are two-way fluxes between land and atmosphere and between ocean and atmosphere; and 3) there is only one-way flux from land to ocean, which is more than two orders of magnitude smaller than the two-way fluxes. Our model simulation presented here complements ref. 1 by extending simulations with modified boundary conditions to test the sensitivity of former results.

## 2. Model and Experimental Designs

The “Green” McGill Paleoclimate Model (hereafter MPM) is a six-component (atmosphere, ocean, sea ice, land surface, ice sheet and vegetation) Earth system Model of Intermediate Complexity. The atmosphere component is a sectorially averaged energy-moisture balance model. The ocean component is a 2.5-D zonally averaged model. The MPM has been developed to include biogeophysical feedbacks [7, 32] so that the energy and moisture fluxes and interactions between land surface and atmosphere are considered interactively. However, the biogeochemical feedbacks have not been considered interactively in the model because of the absence of marine biogeochemistry (The carbon cycle is not closed in the model.). The “Green” MPM has been used in studies of Holocene climate changes and carbon cycle dynamics [7, 33-34] with a retreating Laurentide Ice Sheet. The MPM also has been used to study the last glacial inception and glacial abrupt climate changes [35-37],

Following the approach in refs. 33-34, we prescribed a retreating Laurentide Ice Sheet from 8 to 6 kyr BP in our simulations. The terrestrial carbon cycle module is based on VECODE [5]. VECODE simulates the carbon stored in live vegetation and soil when forced by the climatic conditions (e.g., temperature and precipitation) in the model. The atmospheric CO<sub>2</sub> concentration used in VECODE will have only a fertilizing effect on the net primary productivity. In addition to the atmospheric CO<sub>2</sub>, annual mean temperature and precipitation control the value of annual net primary productivity. The pre-industrial, mid-Holocene (6 kyr BP), and 8 kyr BP terrestrial carbon cycles in the “Green” MPM have been validated in ref. 6, and are in good agreement with other modeling studies [5-6] and observations [38-39].

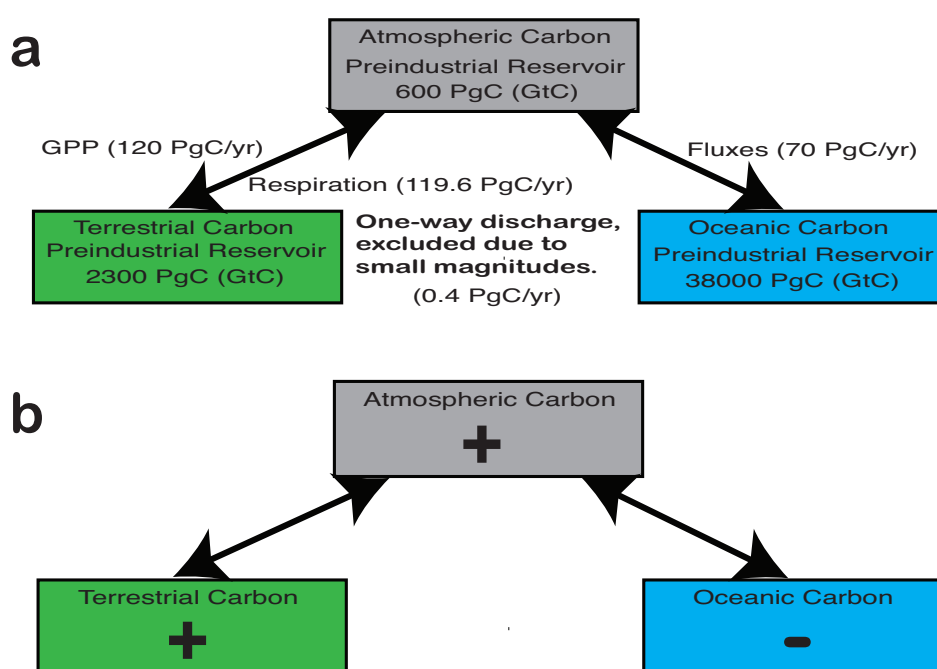
The atmosphere, land surface, and sea ice components of the “Green” MPM, together with VECODE, are first spun up for 60 years under the forcings of (1) monthly mean insolation at the top of the atmosphere at 8 kyr BP [40], (2) the zonally averaged monthly sea surface temperature climatology, and (3) the reconstructed atmospheric CO<sub>2</sub> concentration from the Taylor Dome ice core (260 ppmv). This spin-up represents the forcing conditions and a quasi-equilibrium state at 8 kyr BP [7, 33-34, 41]. The ocean component is next coupled with the aforementioned four components using flux adjustments. The final equilibrium state of 8 kyr BP is reached after an additional 5000 years of integration. After the 5060-year spin-up, the “Green” MPM is subject to an 8000-year transient simulation under the forcings of varying insolation, the reconstructed atmospheric CO<sub>2</sub> concentration from the Taylor Dome ice core, and a prescribed retreating of Laurentide Ice Sheet. The development of Holocene NP is prescribed as a separate and inert carbon reservoir.

## 3. An Inverse Method and Prescribed NP Developments

Because we do not have the marine biogeochemistry module in the “Green” MPM, we have applied the inverse method as developed in ref. 7 (figure 1). Figure 1a illustrates the schematic diagram of pre-industrial carbon cycle dynamics. On the timescale of interest, there are three major players in the global carbon cycle, i.e. without considering the carbon exchanges between rocks and the atmosphere and the anthropogenic land-use and land-cover changes. Furthermore, if we exclude the one-way discharge from land to ocean as in studies of refs. 5-6, we can demonstrate that when both the land and atmosphere carbon storages increase (positive signs in figure 1b), the only source for both of those increases must come from the ocean (negative sign in figure 1b). This is mainly because the ocean

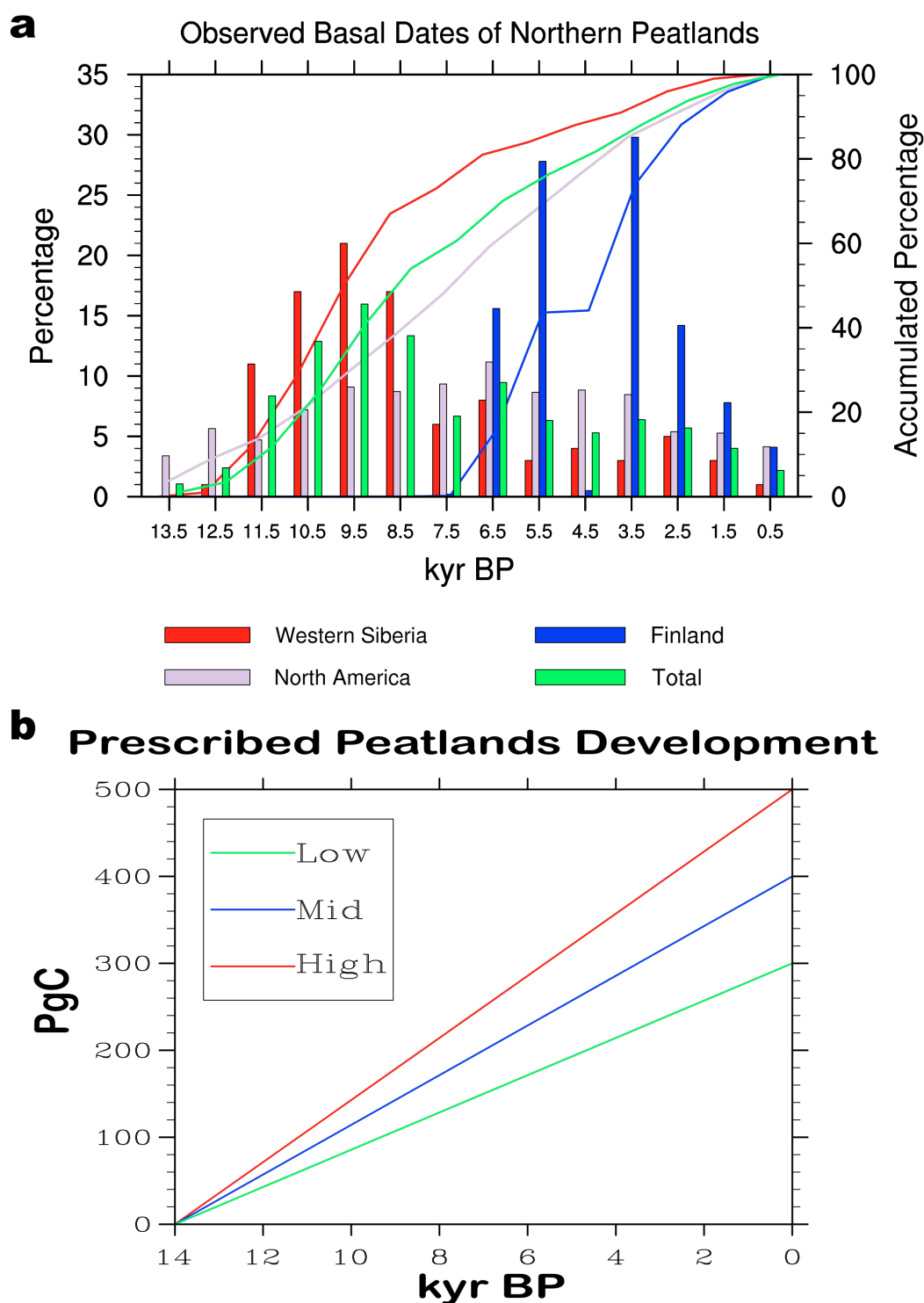
could not directly supply carbon to land without the help of the atmosphere. Under other circumstances, we cannot uniquely determine the source of the atmospheric carbon increase without additional assumptions [7, 41]

### Diagram of Global Carbon Cycles and Inverse Methods



**Figure 1.** The schematic diagram of global carbon cycle dynamics with estimated pre-industrial storages and fluxes from the recent Intergovernmental Panel on Climate Change report (a), and an example of our inverse method showing the relative changes of carbon storage in three major reservoirs (b). The positive (negative) sign corresponds to carbon sink (source) in the global system.

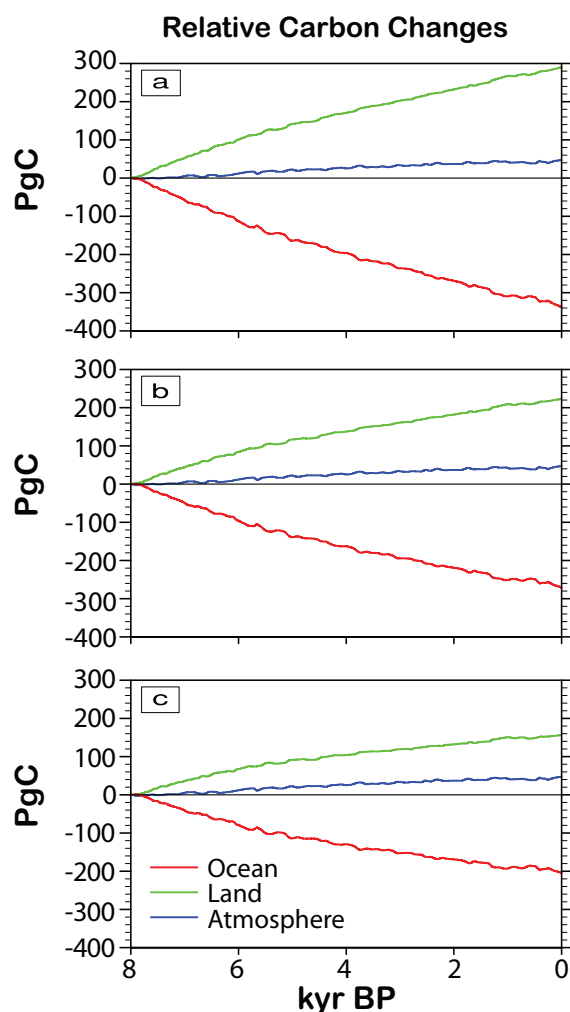
NP have accumulated carbon through the Holocene [21-23, 42] with estimated present-day storages of 300-500 PgC [e.g., 17-18, 26]. Recent studies have advanced our understanding of Holocene NP dynamics in Western Siberia [16], North America [19, 24], and Finland [27]. Figure 2a shows the relative basal date frequencies (percentage) and accumulated percentages for the above-mentioned three regions as derived from those studies. To generate a weighted-averaged total percentage of accumulated basal-date (radiocarbon dates of the deepest/oldest peat in a peat core) frequency, we have assumed a relative area weighting of 10:5:1 for Western Siberia, North America, and Finland [42], respectively. To simplify our prescribed NP development (figure 2b) during the Holocene, we have assumed that (1) NP expansion is proportional to observed basal date frequency, and the total area is thus calculated as a linear function of basal dates (figure 2a, total frequency); and (2) the uptake rate per unit area is and has been constant, and thus the total carbon uptake scales linearly with peatland area [42]. Although in reality, NP growth is nonlinear and many factors have controlled its development through the Holocene, the slow but persistent carbon uptake from NP is a reasonable simple assumption. In particular, we prescribed three developing curves (figure 2b), which correspond to three estimated present-day NP carbon storages of 500, 400, and 300 PgC.



**Figure 2.** The observed basal date frequency of the NP for Western Siberia (red), North America (light blue), Finland (blue), and total (green) (a), and three idealized, prescribed NP development curves in our modelling study (b). Notice that the solid curves in (a) correspond to accumulative percentages of the observed basal date frequency with the same colour coding (right Y-axis).

#### 4. Results

Here we only focus on the effect of the Holocene NP development on global carbon cycle dynamics (see detailed results in ref. 1). Ref. 7 indicated that from 8 to 6 kyr BP, both terrestrial and atmospheric carbon storages were increasing, and the only source they could determine for those increases was the ocean. Because of the late-Holocene desertification of the Sahara and boreal forest retreats, they could not uniquely determine the source of the atmospheric carbon increase from 6 to 0 kyr BP. Additional assumptions were made to partition the source of atmospheric carbon into the land and the ocean in ref. 7. However, if the slow but persistent development of NP is considered, the small release of carbon from the Sahara and boreal forest diminishes. Figure 3 shows estimates of the relative carbon storage changes in land (VECODE plus prescribed NP trajectories, green curves), atmosphere (ice core data, blue curves), and ocean (red curves, assuming global carbon conservation during the Holocene). Based on the inverse method, it is clear that, without considering anthropogenic land-use and land-cover changes, the effect of NP has been to sequester a large amount of carbon from both the atmosphere and the ocean. This sequestration makes it clear that over the past 8000 years, both land and atmosphere carbon storages have increased, and the sole source of these increases is the ocean. Because the global sea surface temperature only varies about 0.2°C in our model simulation (figure not shown here, but in ref. 1) and observations (see, e.g., ref. 10), we further suggest that the deep ocean sedimentation pump (through calcite carbonate compensation) is the main source for land and atmospheric carbon increases if we do not include the coral reef buildup theory [43] and the anthropogenic hypothesis [13].



**Figure 3.** The relative carbon storage changes of land (VECODE and prescribed NP), atmosphere (ice core retrievals), and ocean (inferred assuming global carbon conservation). (a) corresponds to the red curve in figure 2b, (b) corresponds to the blue curve in figure 2b, and (c) corresponds to the green curve in figure 2b.



## 5. Summary and Future Work

Previous studies [2-8] have not been able to unambiguously identify the source of the atmospheric carbon changes in the Holocene (up to 8 kyr BP). However, based on three prescribed linear growths of NP (figure 2b), we have found, without additional assumptions, that the ocean is the sole source of the 20 ppmv CO<sub>2</sub> increase in the atmosphere over the past 8000 years. Our study provides the first-order effect of NP in Holocene carbon cycle dynamics. However, there are uncertainties in our current study, which provides the guidance for future studies of peatlands and Holocene carbon cycle dynamics.

The uncertainties related to our model simulations are mainly caused by the terrestrial vegetation responses to climatic forcing in both boreal forest and the Sahara/Sahel regions. For example, VECODE as an empirically-based land biogeochemistry module has large uncertainties in its simulation of the abrupt ecosystem collapse in mid-Holocene North Africa [44-46]. However, these uncertainties are not critical to the interpretation of our results, as the overall magnitude of NP carbon uptake is large. In addition, the radiative forcing of atmospheric CO<sub>2</sub> concentration is considered, but still contains large uncertainties in the model, which may change our results for the overall sea surface temperature variation in the Holocene.

Our prescribed NP development is highly idealized and is based on the present-day estimated total carbon storage of NP, and previous studies of NP initiation dates. However, large regions of NP do not have well-constrained basal dates. Even with well-constrained basal dates, carbon accumulation rates have varied considerably in many peatlands during the Holocene in response to varying climate conditions [47-48]. While the realistic NP development is unavailable and uncertain, the most significant effect of its growth is the uptake of carbon, and this effect changes the long-term debates regarding the potential carbon source from terrestrial ecosystem.

Our sensitive tests here show that under modified boundary conditions, the results of ref. 1 are robust. Therefore, NP development played an important role in Holocene carbon cycle dynamics. The centerpiece of the Holocene anthropogenic hypothesis is to claim that humans took control of atmospheric CO<sub>2</sub> and CH<sub>4</sub> trends thousands of years ago because of perturbations from land-use and land-cover changes [13-15]. However, without constrained magnitudes of those changes, it is still difficult to add this hypothesis into our model simulations. Nevertheless, our fundamental goal is to introduce interactively-coupled marine carbon dynamics and a dynamic peatland module so that the biogeochemical feedbacks (interactions) can be considered in future simulations of global carbon cycle dynamics in the Holocene.

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